Cablegation VI. The Waterbrake Controller

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This article is reprinted from the TRANSACTIONS of the ASAE (Vol. 28, No. 6, pp. 1957–1960, 1985)
Published by the American Society of Agricultural Engineers, St. Joseph, Michigan

ABSTRACT

THE waterbrake was developed as a low cost means of controlling the plug speed in the cablegation automated surface irrigation system. The waterbrake is a simple hydraulic device requiring no external power source and can be built with locally available materials. The design equations are an extension of those presented in the previous papers. The cable reel design is also discussed.

INTRODUCTION

Cablegation is a new method of automating surface irrigation using gated pipe for conveyance and distribution. The system has been described in detail in previous papers (see references). Automation is achieved by means of a cable-controlled plug which moves through the pipe at a predetermined rate, thus continuously moving a set of water across the field. Water flows from the outlets upstream from the plug.

Water pressure in the pipe provides the force necessary to move the plug. The controller can be any device which unwinds the cable from a reel at a desired rate, usually between 2 and 30 m/h. Two types of controllers are possible: (a) those which provide external power to turn the reel such as an electric motor and gear train, and (b) those which act as a brake or energy dissipator (the waterbrake is of type b).

This paper assumes that the system has been designed and the cable force and desired plug speed are known. Complete cablegation design equations are given in Cablegation V (Kincaid, 1984).

WATERBRAKE CONCEPT

The waterbrake is a simple hydraulic device utilizing the flow of liquid through orifices to dissipate the energy created by the moving plug. The waterbrake is a tubular closed loop shown schematically in Fig. 1, and as it is normally constructed of plastic pipes and elbows in Fig. 2. The pipe loop is supported by a rigid frame attached to a horizontal shaft, and rotates in a vertical plane. It is filled about half full with liquid. Plates containing orifices or valves divided the loop into two equal-sized compartments. The cable reel is attached to the shaft which transmits torque to the loop frame. As torque is applied, the frame begins to rotate, and the liquid weight is shifted to one side until its weight balances the applied torque. If the valves are open, the water flows, allowing the plates to rotate at a constant average speed. Fig. 3 shows a simple plate valve designed to fit into a pipe joint. Normally, two plate valves are used and are located 180 deg apart in the pipe loop. The pipe loop is rigid and is attached to the frame with steel strap clamps at four points. The support frame consists of a hub with four arms of steel angle (3 mm x 38 mm x 38 mm).

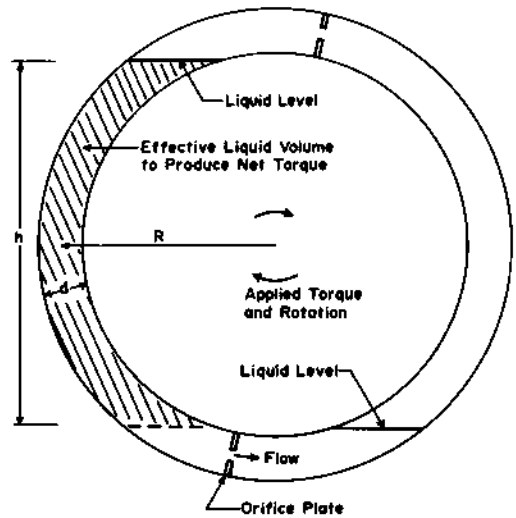

Fig. 1—Schematic of waterbrake concept.

WATERBRAKE DESIGN

The controller can be designed to handle any desired range of cable force and speed. The cable force is determined by the computer model or the equations described in Cablegation V (Kincaid, 1984) and is a

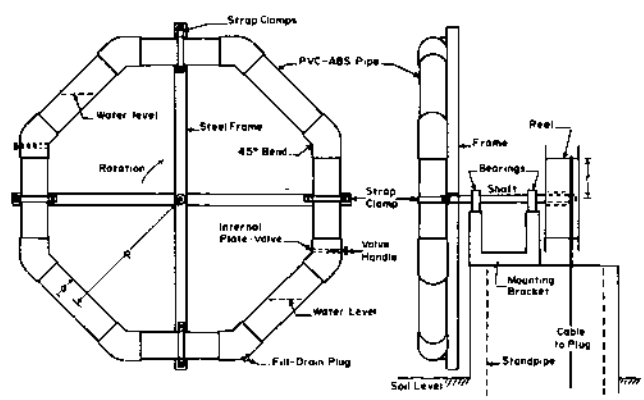

Fig. 2—Octagonal waterbrake.

Article was submitted for publication in April, 1985; reviewed and approved for publication by the Soil and Water Div. of ASAE in September, 1985.

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Acknowledgment: The author wishes to thank Mr. Asael Dilworth, Dilworth Welding and Machine Shop, Hansen, ID, for designing the plate valve shown in Fig. 3.

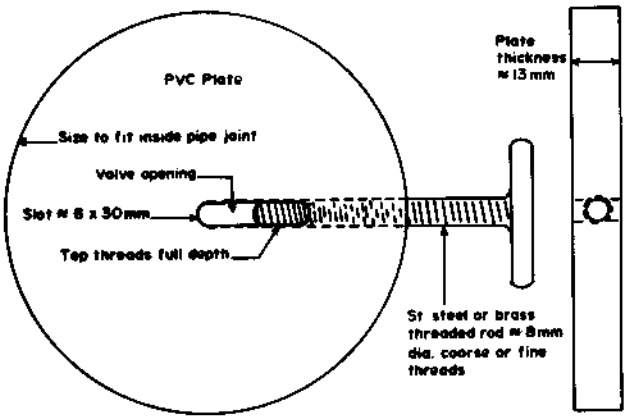

Fig. 3—Detail of plate valve for waterbrake.

function of cablegation pipe diameter, pipe slope, total flow, outlet size, outlet spacing, and riser height if the pipe is buried.

Assuming that the maximum expected cable force, f, in N (lb) is known, the maximum torque on the frame is,

$$T = fr/S \quad [1]$$

where T is the torque on the waterbrake, N-m (lb-in.)
r is the cable reel radius, m (in.)
and S is the ratio of waterbrake speed to reel speed.

The speed ratio, S, is 1.0 if they are attached together as shown in Fig. 2, but can be greater than 1 if they are coupled by gears or sprockets to increase the torque resisting capacity of the waterbrake.

The pipe loop is then designed to counterbalance the maximum torque. The waterbrake will develop maximum torque when the loop is one-half full of water. Referring to Fig. 1, the torque is produced by the force on the submerged orifice plate. That force is the product of the plate area and the pressure difference across the plate. The torque then is the product of the force and the waterbrake radius, or

$$T = 9808\,(\pi\, d^2/4)\, h\, s\, R \quad [2]$$

where R is the waterbrake radius to pipe centerline, m
d is the inside diameter of the waterbrake pipe, m
h is the head across the orifice, m
s is the specific gravity of the liquid
and the constant gives torque in N-m.

The maximum torque, T_m, is produced at a head of $h=2R-d$, therefore

$$T_m = 7703\, d^2\, (2R\text{-}d)\, R\, s. \quad [3]$$

Since d is usually small relative to R, a simpler version of the torque equation can be derived by selecting $h=1.4R$ as the maximum allowable head, to provide a factor of safety of 20-30%. This results in

$$T_b = K_1\, d^2\, R^2\, s \quad [4]$$

where T_b is allowable torque, N-m (lb-in.) and $K_1=10784$ for SI units or $K_1=0.04$ for T_b in lb-in., and d and R in inches. For design purposes, equation [4] is recommended since R can be easily solved for, given T_b and d.

If the pipe and elbow system indicated in Fig. 2 are used, the pipe lengths are cut to produce the required radius, R. Commonly, a radius of 0.6 m (24 in.) and pipe size of 0.1 m (4-in. I.D.) or 0.15 m (6-in.) are used. PVC or ABS pipe with about 6 mm wall thickness (Schedule 40, IPS size) is recommended.

A $CaCl_2$ solution can be used to increase the density of the liquid and prevent freezing. A mixture of 50 g of $CaCl_2$ per 100 g water will produce a solution with specific gravity of 1.28. Alternatively, a 50% ethylene glycol solution has a specific gravity of about 1.06.

Initially, several waterbrakes were built using a square shape rather than octagonal to minimize the cost of the fittings. However, it was found that there was an inherent hydraulic imbalance due to the square shape which caused the rotation to stop if the cable force decreased too much due to increased plug friction at joints. Also, for a given maximum radius, the octagonal shape will handle about 40% more torque than the square shape. Round waterbrakes were also tested but offered little advantage over the octagonal shape. The octagonal shape, which can be made from standard pipe fittings, is therefore recommended.

The valves must be sized to provide the required range of plug speed. The desired maximum rotation speed of the waterbrake frame may be determined as follows. The plug travel speed, P, in m/min (ft/h) necessary to apply a given gross water application is:

$$P = K_2\, Q/(EG) \quad [5]$$

where Q is total flow to the system, L/min (gal/min)
E is furrow length, m (ft)
G is gross water application, mm (in.)
and K_2 is a constant equal to 1 (96.3).

The rotation speed of the frame, w, in rev/min is given by

$$w = K_3\, PS/r \quad [6]$$

where K_3 is a constant equal to 0.159 (0.0318).

Referring to Fig. 1, the rotation rate $w=q/V$ where $q=CAh^{1/2}$ is the flow rate through the orifice, A is the area of the orifice, C is an orifice coefficient (an orifice flow coefficient of 0.7 was assumed), h is the head across the orifice, and $V=(\pi d)^2R/2$ is the volume of the toroid. When these relationships are combined with equation [2], h is eliminated and the valve opening area, A, mm^2 ($in.^2$) is given by,

$$A = K_4\, w\, d^3\, R^{1.5}\, T^{-0.5}\, s^{0.5} \quad [7]$$

where K_4 is a constant equal to 2.31×10^6 (7.07×10^{-4}).

The maximum valve opening should be selected about 20% larger than the size calculated by equation [7] to ensure that the maximum desired speed can be obtained. The valves can then be adjusted to slow the rotation to any desired speed less than the maximum, or to stop the rotation completely.

The valve shown in Fig. 3 is designed to produce a linear relationship between opening area and number of screw turns. This produces a linear calibration between rotation speed and number of screw turns for a constant

applied torque. The final calibration is accomplished in the field while a system is operating.

Equation [7] can be rearranged to determine speed as a function of torque or cable force. The speed is proportional to the torque to the 0.5 power, when the unit is approximately one-half full. Thus, the plug speed is proportional to the square root of cable tension. This effect is desirable for situations where the total flow varies or where outlet sizes are varied on variable-furrow length fields. When inflow rate increases or outlet size decreases, the set width and pressure on the plug increases. The plug speed changes automatically to partially compensate for the changing set width to maintain a more nearly constant inflow time to each furrow.

For systems having a variable pipe slope, the cable tension can vary significantly, and special reel designs are required to reduce plug speed changes. With an increasing pipe slope, a narrow reel can be used so that the effective reel radius decreases to compensate for the increasing cable tension. If the pipe slope decreases, a compound reel can be used so that the cable will transfer to successively larger reels as the cable unwinds and tension decreases. A compound reel consists of two or more adjacent reels of different sizes on the same shaft. The cable is wound up on the reels in reverse order. For odd-shaped fields with variable furrow length, compound reels can be used to increase the plug speed as furrow length decreases.

Equations [1], [6], and [7] can be combined and solved for the reel radius,

$$r = K_5 \, SR \, d^2 \, (P/A)^{2/3} \, (s/f)^{1/3} \quad [8]$$

where K_5 is a constant equal to 5131 (0.0008).
Equation [8] is useful for design of compound reels and is valid as long as the allowable torque is not exceeded. In general, the waterbrake parameters, R, d, S, and A remain constant, while the cable force, plug speed, and reel radius are changed for different field sections (see example below).

MINIMUM REEL WIDTH

As the plug moves across the field, the effective reel radius (and circumference) decreases, and, with a constant cable force, (actually, the cable drag tends to increase the cable force: see below), the torque decreases, causing the plug speed to decrease. In order to minimize this effect, it is recommended that the reel be wide enough so that the change in effective radius (due to cable volume) is less than about 10%. With this criterion and assuming the effective cross sectional area of the cable is c^2 where c is cable diameter, mm (in.), the minimum reel width, W, m (in.) is given by

$$W = K_6 \, L \, c^2/r^2 \quad [9]$$

where L is the total length of cable (field width), m (ft)
and K_6 is a constant equal to 1.5×10^{-6} (18).
Fig. 4 shows a reel design which allows the reel radius and width to be easily changed. This allows one size waterbrake to be used with different systems having a wide range of cable force. When the required reel width is large, or the cable force is larger, a bearing should be

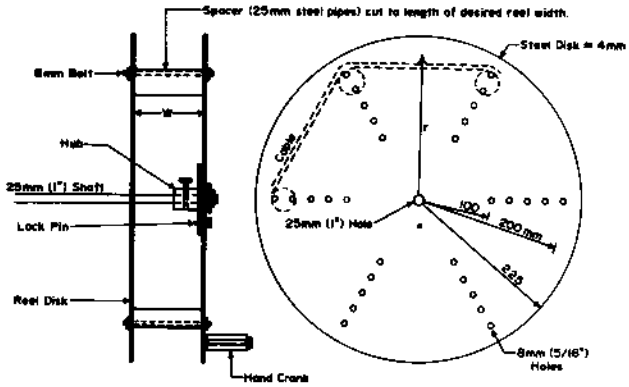

Fig. 4—Adjustable reel for use with a waterbrake cablegation controller.

placed on both sides of the reel. A release mechanism must be provided to disconnect the reel from the waterbrake for rewinding the cable.

CABLE DRAG

The flowing water in the cablegation pipe upstream from the plug exerts a drag force on the cable which tends to increase the cable force on the reel. This force increases as the cable is released from the reel, and tends to compensate for the decreasing reel radius. The drag force is proportional to the square of the water velocity and the surface area and roughness of the cable. Upstream of the flowing outlets, the flow is uniform open channel flow, and Manning's equation can be used to determine average velocity in terms of the hydraulic radius and slope. The hydraulic radius is approximately 0.3 times the pipe diameter, when the pipe is flowing at least half full. The drag force can then be determined approximately by the equation

$$F = K_7 \, c \, D^{4/3} \, S_o \quad [10]$$

where F is the drag force per unit length of cable, N/m (lb/ft)
D is the pipe diameter, mm (in.)
S_o is the pipe slope,
and K_7 is a constant equal to 0.003 (0.4).

The constant, K_7, includes the roughness factor and was determined by field measurement of cable drag using polyethylene twisted cables of about 3 mm and 6 mm diameter of the type used in most cablegation systems. If the estimated cable drag is small relative to the plug force when the cable is fully extended, it may be ignored on the reel design. However, if the cable drag is sufficient to cause the plug speed to increase, the width of the reel may be decreased to produce a nearly constant plug speed.

Plug friction reduces the cable force and is difficult to predict but usually is small and nearly constant. If plug friction is found to be significant, the reel radius may be increased to maintain the desired range of plug speeds.

DESIGN EXAMPLE

An example will illustrate the waterbrake design. A cablegation system design produced a cable force of 350 N. The waterbrake is to be designed for direct drive, S=1. A reel radius of 0.15 m is chosen so the torque is 52.5 N-m. If 0.1 m diameter pipe is chosen, and water is

the liquid, the required waterbrake radius, R, is calculated by equation [4] to be 0.70 m. If the cable diameter is 3 mm, and the length is 400 m, the reel width from equation [9] is 0.24 m. If the pipe size is 200 mm, the pipe slope is 0.01, the length of cable in the flowing water about 350 m, the cable drag is 36 N. This drag increases the cable force about 10% which nearly balances the 10% decrease in reel radius built into equation [9], so the torque and waterbrake rotation speed should remain nearly constant. The plug speed will still decrease about 10% due to reel radius. The total flow is 4000 L/m, furrow length is 400 m and a 100 mm gross application is desired. The required plug speed is 0.1 m/min and the reel rotation speed is 0.11 rev/min. The valve opening A, from equation [7], is 20.5 mm^2.

As an example of compound reel design, suppose that this system is extended to an adjacent field where the pipe slope decreased, the furrow length is 300 m, and the design for the second section resulted in a new cable force of 200 N. The plug speed for this section is 4000/(300x100)=0.13 m/min, assuming the same gross application is required. The parameters A, d, and R are unchanged. Using equation [8], a new reel radius is computed, r=0.21 m. If the second section is 400 m in length, and the cable size is 3 mm, the required reel width is 0.12 m. Thus, the compound reel would have radii of 0.15 and 0.21 m.

DISCUSSION

During the 1985 irrigation season, approximately 35 waterbrakes were in operation on farm systems. About 80% were direct drive (S=1). Where the cable force exceeded about 800 N (180 lb), a 5:1 ratio chain drive was used. The direct drive units cost about $300 and are being manufactured by Dilworth Welding and Machine Shop, Hansen, ID 83334.*

*Manufacturers' names are presented for the benefit of the reader and do not imply endorsement by the USDA.

Several farmers have reported that the direct drive waterbrakes operate satisfactorily, but it is time consuming to measure and adjust the speed since one revolution typically takes 10 to 20 min. For this reason, it may be desirable to use a speed ratio of about 5:1 to speed up the waterbrake. This also allows use of a smaller waterbrake. The chain drive costs about $50-100 more than the direct drive. The chain drive provides additional flexibility since the sprocket ratio can be easily changed. Gear drives with ratios up to 20:1 have been tested, but the cost and gear drive friction are problems with high ratios. Also, it is recommended that sealed ball bearings be used to minimize friction.

The mounting frame design will vary depending upon the waterbrake and reel design and the base upon which it is placed. The main requirements are to maintain clearance for the waterbrake and to place the reel over the inlet structure in a convenient position for rewinding the cable.

When designing and using the waterbrake, care should be taken to ensure that the torque limit is not exceeded. If this happens, the waterbrake will begin to rotate rapidly and may be damaged or present a safety hazard.

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